RECENT AEOLIAN ORIGIN OF SURFICIAL GYPSUM CRUSTS IN SOUTHERN TUNISIA: GEOMORPHOLOGICAL, ARCHAEOLOGICAL AND REMOTE SENSING EVIDENCE

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ABSTRACT

Recent quarring of the surficial gypsum crusts adjacent to Djebel Sidi Bou Hellas has revealed sections typically showing a discontinuous surface gravel cover underlain by more than 7 m of microcrystalline gypsum. The location, elongate shape, form in cross-section and chemistry of this deposit suggests an aeolian origin, whereby aeolian sands have been trapped against a glacis d'erosion terrace, and subsequently consolidated by meteoric waters.

One gypsum quarry revealed a midden and the remains of a Roman dwelling now buried within the crust. A radiocarbon date of organic matter in the midden and a Roman coin found within it suggest an age of AD 324–345 for the deposit. This is the first firm date for a surficial gypsum crust in southern Tunisia and the age is surprisingly young. Previous studies have speculated on phases of crust development between the Villefranchian and early Holocene but none since.

Remote sensing and field evidence show that gypsiferous sands are currently deflated from the dry parts of the mudflats of Chott Fedjaj. They are subsequently transported in a southwesterly trajectory and trapped against glacis on the southern margins of Chott Fedjaj, forming contemporary analogues of the Roman deposit. Sands that are not trapped form dune fields and sandflats where gypsum crusts appear to be forming today. If the source area of gypsum sands has remained constant since Roman times, then the predominant wind direction has moved 45° to the southwest since then. The other possible source of aeolian gypsum for the Roman deposit, the vast mudflats of Chott Djerid, involves an even greater change in predominant wind direction. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

This paper provides new evidence on both the mode of formation and the age of surficial gypsum crusts by studying archaeological, remote sensing and geomorphological evidence from surficial gypsum deposits in the Chott Fedjaj basin and northern part of the Chott Djerid basin, southern Tunisia (Figure 1). The research focuses on crusts located on and adjacent to glacis near Tozeur, where a Roman site is located near and within an extensive deposit of surficial gypsum crusts.

Gypsum crusts are common phenomena in arid areas (Watson, 1983), where they form an important resource as a road building material, but also have significant detrimental effects on the viability of agricultural and urban areas. Problems associated with gypsum crusts include increased runoff due to their impermeable nature, which can lead to a loss of soil fertility, and extreme damage to building materials due to salt weathering. There is much debate about the processes that cause gypsum crust formation, their age and hence their long-term influence on the landscape.

There are five types of surficial gypsum in southern Tunisia: playa mudflat sediments, active aeolian sand dunes, sandflats studded with nebkas, consolidated inactive dunes, and crusts. This paper considers the origins of surficial gypsum crusts that are a prominent feature of the landscape. The surficial crusts consist predominantly of gypsum and quartz, though minor amounts of calcite are sometimes found replacing gypsum (Watson, 1988). The texture is commonly microcrystalline and the surface is often covered in gravel and polygonal cracks that divide the crust into roughly hexagonal columns.

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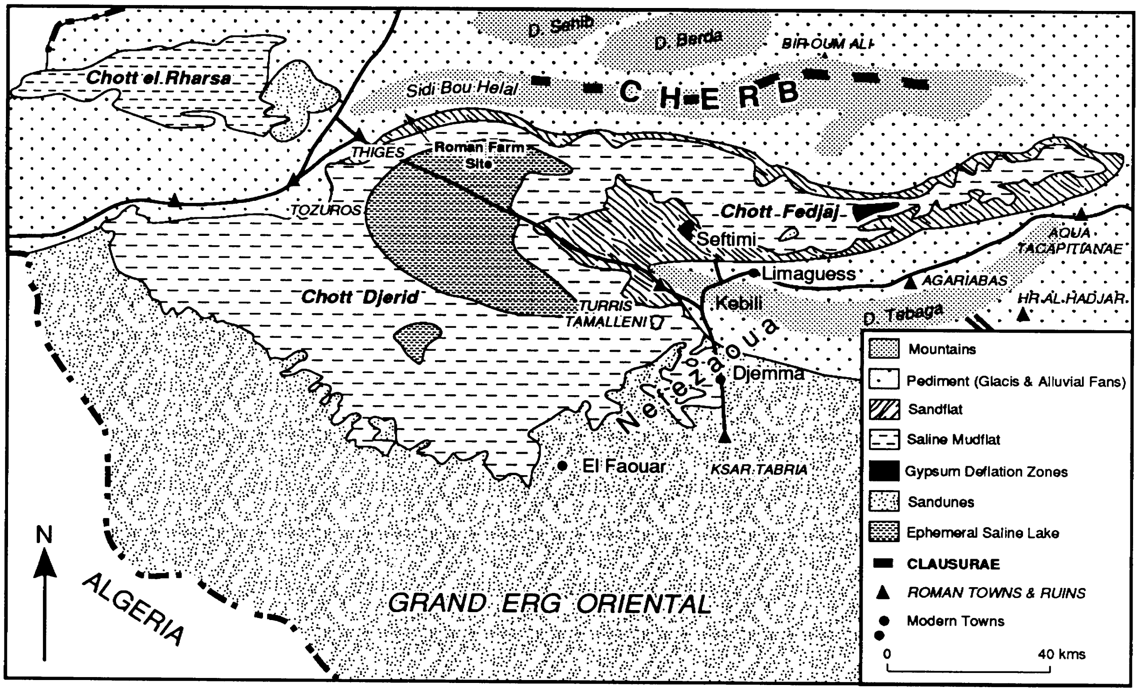

Figure 1. Location of the study area and some of the geomorphological, sedimentological and archaeological features of the region. The depositional and erosional environments are simplified from Bryant *et al*. (1994) and Drake *et al*. (1994). For the sake of simplicity, minor environments such as spring deposits are not marked

Four theories have been proposed for surficial microcrystalline gypsum crust formation in Southern Tunisia. Bureau and Roederer (1961) suggest that capillary rise of soil moisture has caused the build-up of gypsum at or near the surface; however, this model is unlikely to be applicable to the glacis deposits considered here as they are a considerable distance above the water table. Coque (1962) noted that gypsum crusts are found in all topographic locations and invoked aeolian gypsum deposition to explain this, the likely source of the gypsum being dust deflated from playas and subsequent consolidation caused by meteoric waters. Watson (1985, 1988) agreed that the gypsum is probably derived from playas, but points out that there is no direct evidence for this. He notes that many of the crusts have a well developed gravel cover which is not readily explained by Coque's model. He suggests that the deposited aeolian gypsum is subsequently leached down the profile and redeposited as illuvial pedogenic crusts. These pedogenic crusts are later exhumed by aeolian deflation to form surficial microcrystalline crusts.

It has been shown that the downward leaching of gypsum from surficial crusts by meteoric waters is an active process in southern Tunisia today. Vieillefon (1980) studied the concentration of titrium in the water of crystallization of gypsum for surface and subsurface microcrystalline crusts. The results showed that while the subsurface crusts were currently accreting, the surface crusts were not. White and Drake (1993) used remote sensing to show that gypsum sands are currently being deflated from the mudflats of Chott Fedjaj, confirming playas as the source of the gypsum. Consolidation of these sands is currently forming surficial crusts on the sandflat that straddles the margins of Chott Fedjaj and Chott Djerid west of Seftimi (Figure 1). White and Drake (1993) also noted that surficial gypsum crusts seem to be preferentially located on gypsiferous bedrocks and suggested that the bedrock may play a role in long-term crust preservation, either by providing a replenishing source or by promoting gypsum saturation of surface runoff and thus reducing its ability to dissolve other gypsiferous materials.

There has been much speculation and controversy about the age of these crusts. Coque (1962) found gypsum in Villefranchian deposits, but suggests that the majority of gypsum crusts were formed at the end of Pleistocene pluvial periods. le Houerou (1960) argues that they are much older, being formed between the Villefranchian and Tensiftian, but Page (1972) suggests that they are early Holocene because solution of gypsum by rainfall would preclude their long-term preservation. Fontes *et al*. (1983) provide the only dated sequence that contains gypsiferous deposits. Many of these are gypsiferous peat and karst deposits and thus cannot be considered crusts; however, the sand layer that dates at between 20 000 and 40 000 BP has a similar chemistry to surficial crust and could be a buried equivalent.

STUDY AREA

The study area is centred on Djebel Sidi Bou Hellal, a mountain at the western end of the Cherb range (Figure 1). The climate is arid, with an average annual rainfall of 99 mm at Tozeur. Maximum rainfall occurs in the winter months; however, it is extremely erratic both within and between years.

The Cherb range is an elongate anticline situated at the southeastern limit of the Atlas Mountains. It provides the last mountain chain before the great depression that contains the playas Chott Fedjaj and Chott Djerid. Cretaceous rocks form the core of the anticline and consist of marls, sandstones, limestones and gypsum. They dip steeply to the north and south. Adjacent Mio-Pliocene strata unconformably overlay the Cretaceous with a much shallower dip. These rocks are poorly consolidated and incorporate sandstones, shales, limestones, clays, marls and gypsum beds (Burollet, 1967).

Figure 1 shows the geomorphology of the area and the depositional environments of the Chotts. Consolidated Cretaceous rocks form the uplands, while the softer Mio-Pliocene sediments have been planated by erosion into a series of nested pediments known as glacis d'erosion (Coque, 1962). Outcrops of more resistant Tertiary beds form lines of small hills along their strike that lie above these nested planar surfaces (Figure 2A). The glacis are in turn flanked by alluvial fans forming coalescing cone-shaped structures where the streams debauch from the confinement of the glacis. At the base of these fans are the extensive mudflats of Chott Djerid and Chott Fedjaj (Drake *et al*., 1994). The mudflats are commonly moist and contain varying amounts of fine-grained clastic material, gypsum and minor halite. The boundary between alluvial fans and the mudflats is characterized by sandflats where fine-grained material is reworked by aeolian processes forming nebkas and a few small dunes.

METHODS

All the gypsum deposits described here were located by remote sensing and subsequently investigated in the field. Gypsum was mapped by applying a linear mixture model (Settle and Drake, 1993) to the six reflective bands of a Landsat Thematic Mapper (TM) image acquired on 13 September 1987.

Mixture modelling maps the proportion of each surficial material in each pixel of the image by minimizing the following quadratic:

$$(x-Mf)^{T}C^{-1}(x-Mf)+V(f-g)^{T}(f-g) \qquad (1)$$

The method relies on defining a matrix of endmember spectra M. The columns of M are the vectors of radiance values for the purest pixels of each material in the image. f is a vector of unknown proportions, x is a vector of the pixel radiance values, C is a matrix of errors and V is a smoothing parameter. The advantages of using this linear model are outlined in Settle and Drake (1993), while the accuracy of the method applied to this image is outlined by White and Drake (1993). The method appears to produce quite accurate estimates of gypsum abundance because gypsum has spectral reflectance characteristics that are distinctly different from other materials in the image. Comparison of mixture modelling and ground estimates of gypsum produces a correlation (r^2) of 0·86 (White and Drake, 1993).

Field investigations of gypsum deposits involved measuring, mapping and sampling sections in the field. Sections were mostly taken at gypsum quarries; however, the quarried deposit was traversed for about 7 km of

(a)

(b)

(c)

Figure 2. (a) Outcrops of more resistant Mio-Pliocene strata form lines of hills along their strike that lie above the nested planar surfaces of the glacis d'erosion. Here the hills form the divide between the glacis and the alluvial fans. (b) A massive microcrystalline crust exposed in one of the gypsum quarries. The quarry wall is about 7 m high, and the base of the deposit has not been reached by the excavation. (c) Gypsum deflation zone on the northern margin of the mudflats of Chott Fedjaj (location shown on Figure 1). This deflation zone is characterized by a soft puffy surface with a lag of large lenticular gypsum crystals

its 30 km length in order to locate cross-sections through the deposit. Samples were subsequently analysed by X-ray diffraction (XRD) to estimate of gypsum abundance. After location of the Roman dwelling, it was mapped using a 30 m tape and artefacts were photographed in the field for later confirmation of their identification.

The organic material found in one of the quarry sections was dispersed in deionized water, subjected to hot acid washes to remove carbonates, neutralized, dried, synthesized to benzene and measured for C14 content. The stable carbon isotope ratio (C13/C12) was also measured, and corrections were applied and used in calendar calibration to obtain the best approximation of the calendar equivalent age.

REMOTE SENSING AND GEOMORPHOLOGICAL EVIDENCE

The distribution of gypsum as determined by mixture modelling for the Sidi Bou Hellal area is shown in Figure 3, and the location of the image is outlined in Figure 4. In this region all the gypsiferous exposures are microcrystalline crusts and it is clear that gypsum crusts are found in variable but quite high amounts all over the mountain. Figure 5 depicts the distribution of the extensive areas of crust exposure by outlining only large regions that exhibit greater than 50 per cent gypsum. The figure shows the relationship of the main areas of crust to the landforms of the region.

An extensive area of crusts is found overlying Tea Green Marls (Figure 5, region A). These marls contain both clay and gypsum; they are more prone to erosion than other strata, and thus create stratiform valleys on Djebel Sidi Bou Hellal. An elongate region of gypsum crusts is found at the break of slope between the mountains and the glacis (Figure 5, region B). A further long, thin gypsum deposit is found at the boundary between the glacis and alluvial fan (Figure 5, region C). This latter deposit is capped by a thin covering of colluvium at the top, which grades into a discontinuous veneer of gravels towards the base; this was interpreted by White and Drake (1993) as a crust overlying gypsiferous Mio-Pliocene strata because it is adjacent to, and has a similar strike to, the Mio-Pliocene rocks that form the glacis deposits.

Figure 3. The distribution of crusts in the study area as determined by mixture modelling of Landsat TM imagery. Black indicates low proportions and white the highest amounts, which are 65 per cent in this image

An inspection of this deposit in 1994 revealed a series of new gypsum quarries excavated for recent road building in Kriz. Sections exposed in the gypsum quarries showed that the deposit is not directly underlain by Mio-Pliocene strata but is a massive microcrystalline crust that is at least 7 m deep in places (Figure 2B). None of the gypsum quarries exposes the base of the deposit; however, sections through it do occur in a few locations where streams emerge from the glacis into the confined channels of the incised alluvial fans. The cross-section of the deposit (Figure 6) is of a form that is best explained by trapping of aeolian sands against the ridge of

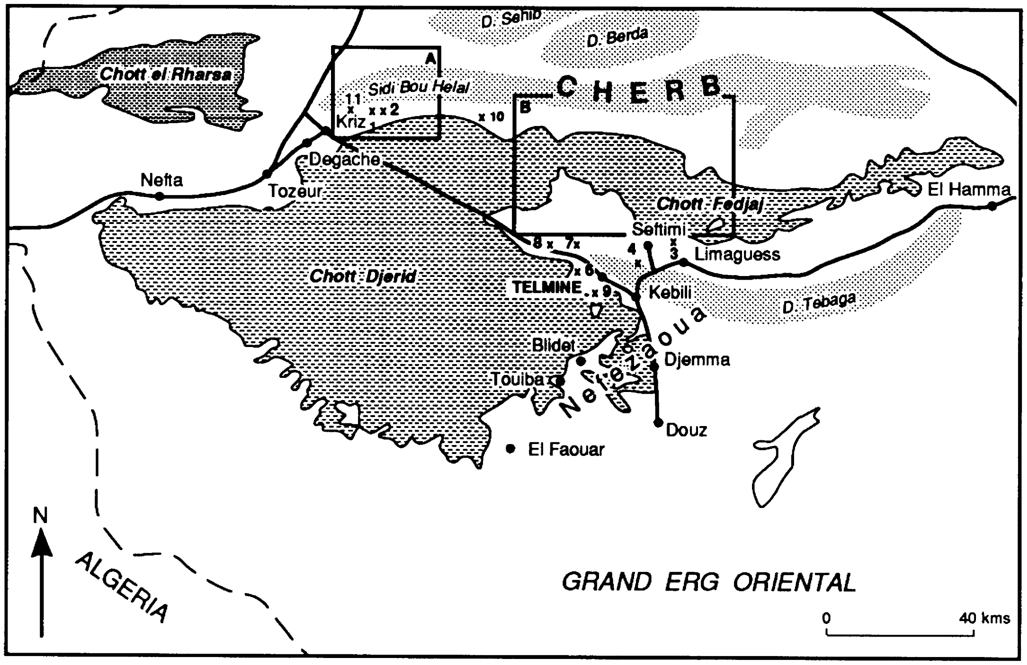

Figure 4. Location of sample sites. The locations of gypsum abundance images derived from mixture modelling of Landsat TM imagery are outlined by rectangles: A for Figure 3 and B for Figure 8. The numbers show the location of sample sites listed in Table I

resistant Mio-Pliocene sediments that marks the start of the glacis. The ridge forms the first significant topographic barrier on the northern margins of Chott Djerid. An aeolian origin would also explain the fact that the depth of the crusts exposed in the quarries appears to be controlled by the height of the glacis surface above the alluvial fan, which is in turn controlled by the resistance of the Mio-pliocene strata to erosion.

The spatial distribution of the major gypsum deposits on Sidi Bou Hellal can also be interpreted as supporting an aeolian origin. The extensive gypsum crusts on the southeastern side of Sidi Bou Hellal are located either at breaks in slope or in valleys underlain by marls. On the northwestern side of the mountain, however, there is less gypsum and major deposits are not located at topographic barriers. This distribution is consistent with the crusts being derived from aeolian material that originated from the Chotts. The sand appears to have been transported in a west or northwest direction; on the upwind side of the mountain it was deposited in valleys that were sheltered from the wind or behind topographic barriers. However, when the sand was on the downwind side it travelled downhill and was not trapped by these obstacles. Thus the observation of White and Drake (1993), that crusts are found preferentially on gypsiferous lithologies such as the marls of Sidi Bou Hellal, appears to occur because of aeolian processes and not the geochemical ones they postulated.

Active aeolian sands are currently being derived from the mudflats of Chott Fedjaj (White and Drake, 1993; Drake, 1992). Deflation zones of gypsum appear to be located on the dryer edges of the mudflats, where the water table is well below the surface in dry periods (greater than 1 m in December 1994). Evidence of deflation is only observed when the sediment contain large gypsum crystals. In this situation the deflation zones are characterized by soft puffy surfaces with a lag of large lenticular gypsum crystals (Figure 2C), and can be readily mapped in the field (Figure 1). The aeolian sands derived from these regions are now transported in a southwesterly direction, and some of this is currently being trapped against similar topographic barriers on the southwestern margins of Chott Fedjaj (Figure 7A), forming contemporary analogues of the deposit that forms the boundary between the glacis and alluvial fan outlined above.

Mixture modelling shows that not all sand is trapped by glacis barriers that fringe Chott Fedjaj. Figure 8 shows the distribution of surficial gypsum in the northern region of the basin of the Chotts (the location of this region is shown in Figure 4). The gypsiferous mudflats exhibit low gypsum proportions owing to their high

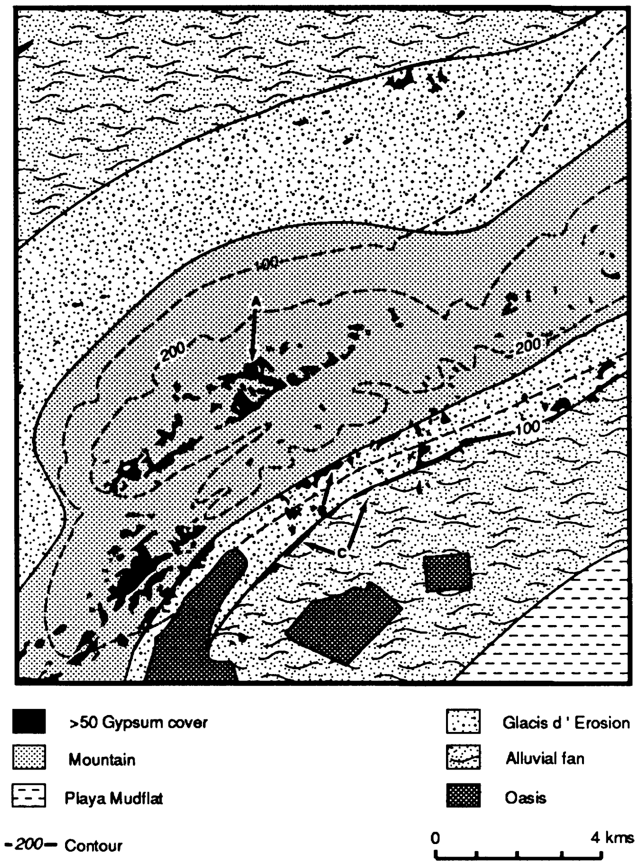

Figure 5. The relationship of the crusts to the landforms of the study area. Only the large regions that exhibit greater than 50 per cent gypsum exposure have been marked. These are regions of well developed microcrystalline crusts

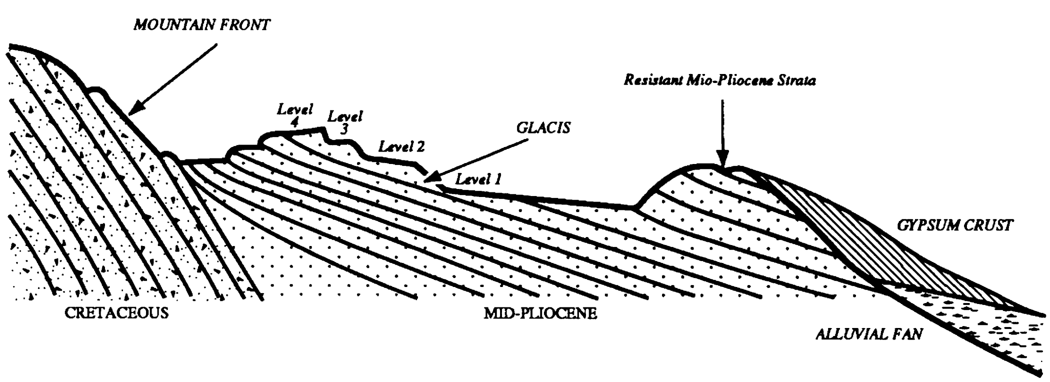

Figure 6. Schematic cross-section of glacis d'erosion and the surficial microcrystalline gypsum deposit. The section is approximately 1·5 km long and orientated in a north–south direction

(a)

Figure 7. (a) A contemporary analogue of the gypsum deposit exposed by quarrying. Aeolian sand derived from Chott Fedjaj is transported in a southwesterly direction until some of it is trapped against the first topographic barrier encountered, a glacis terrace on the southern margins of Chott Fedjaj. (b) (see over) Section of an aqueduct that can be traced leading from an oasis in the bead of the Oued El Kenntaia to the general vicinity of the Roman farm site. (c) (see over) Evidence for reworking of consolidated aeolian sands trapped against a glacis terrace on the southern shores of Chott Fedjaj

moisture content. However, XRD studies of oven-dried samples show that they often have a high gypsum content when dry (Drake, 1992). Much sand is temporarily stored in a dune field on the mudflats before it reaches the glacis on the edge of the Chott Fedjaj (Figure 8, region A). Some sand is trapped behind the glacis terrace (Figure 8, region B); however, most sand manages to transcend these barriers and traverses the sandflat, where it may be trapped by bushes to form phreatophyte mounds and nebkas, or in the lee of spring mounds and oases where it forms deposits whose tails point in the predominant wind direction (Figure 8, region C). If trapped for long enough, this sand may become consolidated and add gypsum to the surficial microcrystalline crust that is currently forming in this region. In some areas the crust is beginning to develop polygonal columnar structures and the surface only differs from the crusts on Djebel Sidi Bou Hellal in terms of the presence of active sand and the lack of gravel cover.

ARCHAEOLOGICAL EVIDENCE

Inspection of the quarries in the linear gypsum deposit excavated for road building revealed a simple stratigraphy of gravel cover underlain by a varying depth of microcrystalline gypsum that showed no beading or any other discernible structures (Figure 9A). However, part of one quarry revealed a more complex stratigraphy (Figure 9B). Here, the gravel cover was thicker than usual (0·75 m) and contained numerous pieces of pottery. Below this, a layer of gypsum crust containing abundant cobbles is exposed to a depth of 1·26 m; this in turn is underlain by a thin layer of organic material (10 cm), and below this is the usual massive microcrystalline

(b)

(c)

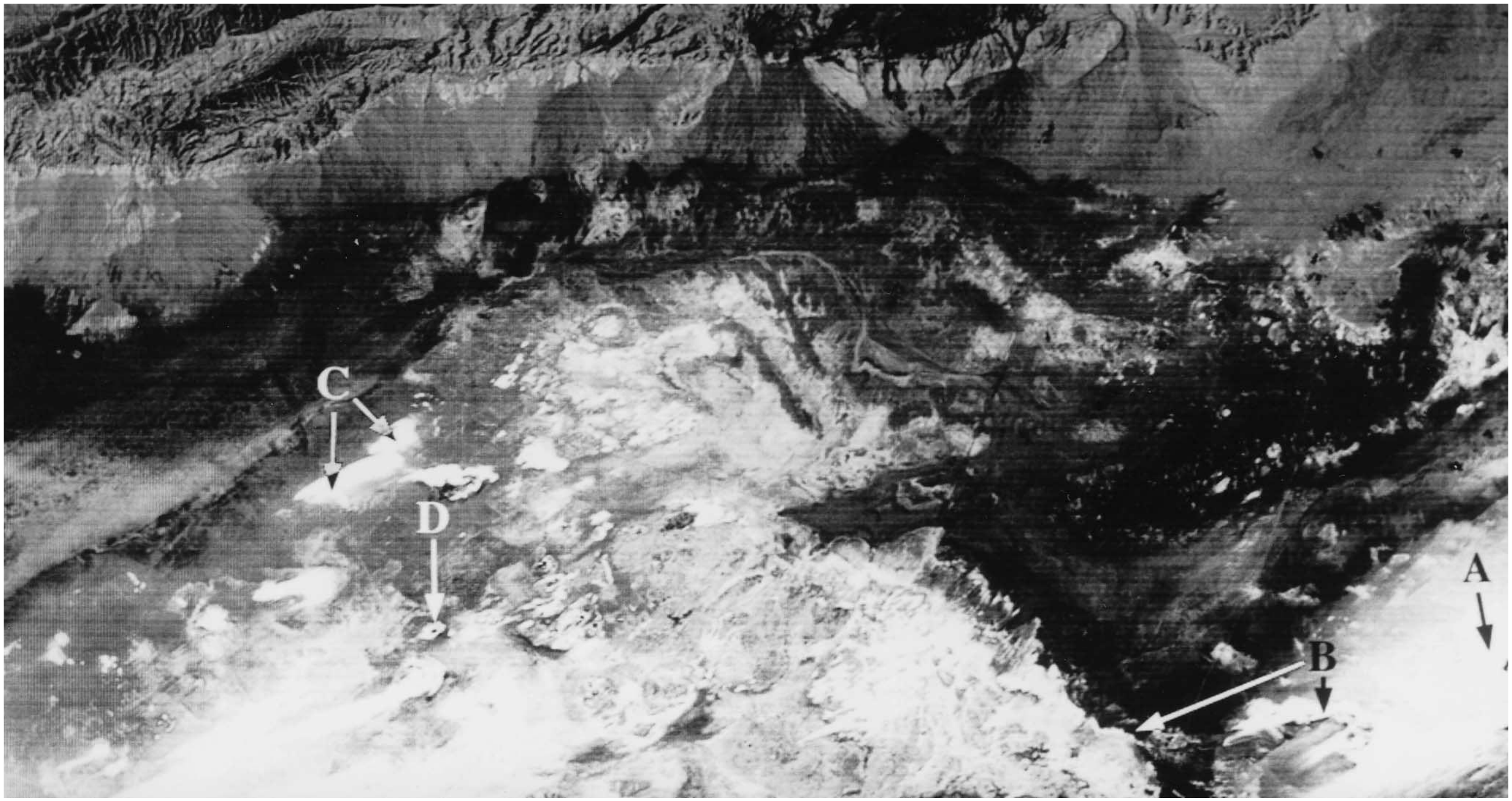

Figure 8. The distribution and abundance of gypsum as determined by linear mixture modelling of Landsat TM imagery for western Chott Fedjaj and northern Chott Djerid (see Figure 4 for location of map). Black indicates low proportions and white the highest amounts, which are about 80 per cent in this image. Regions A, B. C and D are discussed in the text

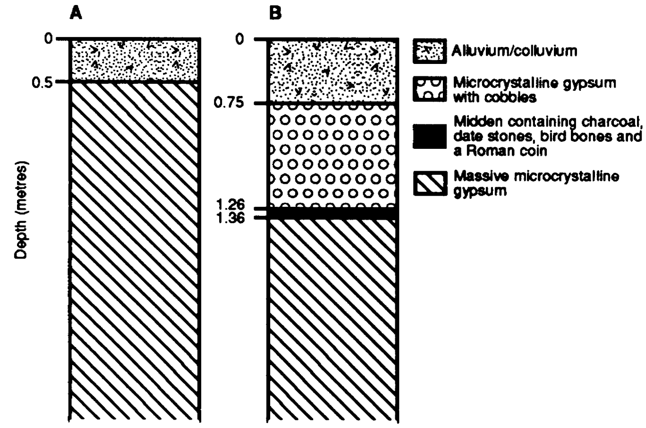

Figure 9. Sections of microcrystalline crusts revealed in the gypsum quarries. (a) Typical section through a microcrystalline crust. (b) Section through crust that revealed Roman artefacts

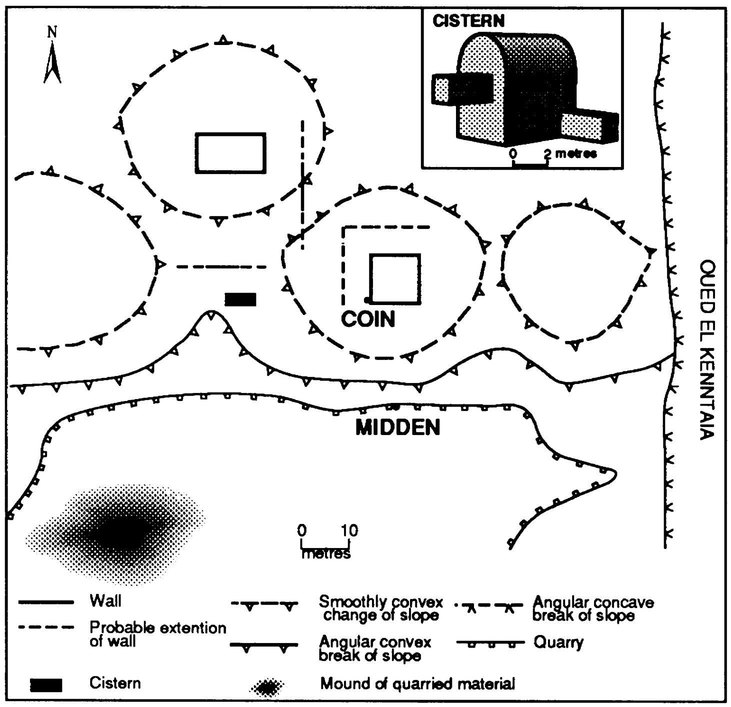

Figure 10. Map of the Roman farm settlement. A diagram of the cistern found at the site is shown as an inset

gypsum. Excavation of this organic layer revealed date stones, bird bones and a bronze coin. The presence of human waste in the organic layer suggests that it is a midden. The coin was weathered but could be identified as Roman (R. M. Reece, personal communication, 1995), having been minted when Constantine II was Caesar (AD 324–330). Bronze coins of this size were probably only kept in circulation until AD 345, when their size and silver content was reduced. After this date they would have been melted down because their bronze and silver content was greater than more recent coins with the same face value. Thus the coin was probably discarded sometime between AD 324 and 345.

The coin provides age constraints for the organic layer: it can be no older than AD 324 but, is unlikely to be younger than AD 345. Radiocarbon dating of the organic layer provided a C13/C12 adjusted age of AD 255 ± 70 (Beta 72089). This age calibrates to a one standard deviation range of AD 230–400 and a two standard deviation range of AD 130–440. The intercept of the calibrated date is AD 330. Thus the radiocarbon date is compatible with the idea that the coin was discarded soon after minting. These recent dates mean that the gypsiferous materials above the midden are much younger than implied by previous studies of gypcrete in southern Tunisia (Coque, 1962; le Houerou, 1960).

Exploration of the area upslope from the midden revealed much evidence of past human settlement (Figure 10). The slope was scattered with broken pottery and another coin was found. Although it was more degraded than the first, markings suggest that it is either a fallen horseman (AD 350–360), or a House of Valentinean (AD 364–378). Thus the site appears to have been occupied in the mid-fourth century. The foundations of numerous walls could be identified, indicating two structures, with parts of what appear to be separate enclosing walls also visible. In close vicinity there was a small hole in the ground that exploration suggests is a cistern with a partially collapsed roof (Figure 10). The cistern is cut into marl and exhibits a tunnel at each end; both are blocked after about 1 m, one with marl and one with angular gypsum crust fragments. Although no water conduit can be traced leading directly to the cistern, sections of an aqueduct can be traced leading from an oasis in the bead of the Oued El Kenntaia to the general vicinity of the site (Figure 7B). The aqueduct and cistern are at least 15 m above the current level of the Oued and there is no evidence of a dam along its course. In addition, the oasis is currently supplied by a borehole and although there are many natural springs to the west, in the region of Kriz, there are none here. Thus how the water was collected and supplied to the aqueduct remains an enigma. These Roman remains probably represent a farm complex, but what type is not clear because of the poor preservation. If most of the original foundations have been identified then it is probably not a Gsur, a fortified farm that was common in North Africa at this time. The farm probably supplied food to the nearby Roman town of Thiges (Figure 1).

The Roman farm may help to explain the gypsiferous cobble layer in the quarry section (Figure 9A). The presence of cobbles above the midden and the absence of both facies in other sections suggest that the cobbles represent rubble from the decay or destruction of the farm dwellings immediately upslope. The presence of a few pottery fragments amongst the cobbles helps to correlate this material to the settlement. The cobbles within the section are heavily weathered and no evidence of hewn stone is preserved in the section outcrop itself; however, the mound of unused quarried gypsum (Figure 10) contains a few hewn blocks of finished limestone that must have been derived from the dwellings, though they lack stratagraphic location within the quarry.

DISCUSSION AND CONCLUSIONS

These findings have implications for theories of gypsum crust formation, their timing and development since then. In addition they provide information on the wind regime at the time the crusts were formed. These topics are considered in turn below.

Theories and timing of crust formation

The theory of capillary rise proposed by Bureau and Roederer (1961) does not lend itself to the Roman farm deposit as it is situated well above the capillary fringe. The model of Watson (1988), whereby aeolian gypsum is deposited on a surface, consolidated, leached down the profile, redeposited in the soils below as an illuvial pedogenic crust, and then exhumed by aeolian deflation to form a surficial microcrystalline crust, does not explain many aspects of this deposit. The gravel cover on this crust cannot be explained by downward leaching and subsequent aeolian exhumation. This scenario would have obliterated the observed form and stratigraphy of the deposit; the Roman farm debris, for example, would be located on top of the deposit and not within it. In addition, the crust is so young there would have been very little time for all these processes to occur. As the surface of the crust post-dates the midden and the cobbles derived from the destruction of the farm, the surface gravel must have been deposited since the farm was abandoned, AD 350 being the earliest possible date. The main reason why Watson (1988) put forward the aeolian deflation aspect of his model was to explain the gravel, which he believed could not be explained by fluvial processes. Here, the presence of gravel on the crust can only

be explained by fluvial and/or colluvial processes, though they must have acted over a surprisingly short period of time. It is possible that the presence of impermeable gypsum crusts promotes the development of a gravel cover by encouraging overland flow.

The model of Coque (1962), whereby aeolian gypsum is deflated from the Chotts and consolidated by meteroric waters, appears to be most applicable to the deposit. The geomorphological and archaeological evidence suggests that aeolian processes alone can best explain the spatial distribution of surficial gypsum, rather than the combination of aeolian and geochemical processes suggested by White and Drake (1993) to explain the preferential occurrence of gypsum crust on gypsiferous rock outcrops. This reinterpretation of the spatial distribution shows that inferring process from the spatial distribution of gypsum, without regard to other evidence, is problematic, as different processes can be postulated that lead to the same spatial distribution.

Mode of crust consolidation

The crust at the Roman farm site, its contemporary analogue in Chott Fedjaj and the spatial distribution of gypsum abundance can provide some detailed information on the transformation of gypsum sand to crust. The angular gypsum crust fragments that block the entrance to the cistern indicate that at least the lower part of this gypsum deposit was consolidated before the cistern was abandoned, and possibly before it was built. There is only evidence of occupation of the site in the mid-fourth century, but a longer occupation cannot be precluded without thorough excavation; however, the known history of Roman influence and occupation in the region can provide a loose range for the length of time the site was occupied. Current archaeological knowledge of the study area suggests that the farm is unlikely to have been built before AD 83–84, when the first roads and civitases were established in the region (Mattingly, 1995). Thus the farm is most likely to have been established between AD 83 and 345, probably towards the later part of this period as the evidence in this paper only shows definite occupation in the mid-fourth century. It is probable that the site was abandoned soon after this, as the region went into decline in the mid-fourth century (Mattingly, 1995); however, it is possible that it was occupied as late as the fifth or even early sixth century. The crust must have been consolidated during or before this time.

The presence of gypsum above the midden suggests that aeolian activity proceeded, possibly continuously and certainly periodically, until after the destruction of the farm (probably soon after AD 350). This is supported by the fact that surficial crusts are found on and adjacent to the farm foundations. Thus it seems that consolidation and accretion of the crust were going on at the same time, indicating that crust consolidation can be rapid. The presence of a ubiquitous gravel on the crust (formed by fluvial/colluvial activity since the crust was deposited), but the absence of continuous gravel layers in any of the quarry sections, suggests that deposition of the whole deposit was rapid. It was certainly quicker than the period of time it takes for the gravel cover to form, which the archaeological evidence suggests is less than about 1500 years, so the deposit cannot have been accreting for an extensive period of time before the occupation of the farm.

Two examples in southern Tunisia show that gypsum sand consolidation can be a rapid process. First, Coque (1962) reports on consolidated gypsiferous nebkas where the sand must have been stabilized since the plant became established. Secondly, consolidation seems to be occurring today on the sands trapped behind the glacis of Chott Fedjaj (Figure 7A). Although the surface is covered by active aeolian sands, in many places there is a microcrystalline gypsum crust below. In addition, in some places above this crust, previously consolidated sands are reworked by the wind to form small yardangs (Figure 7C), indicating that once stabilized, sands can be reworked by the wind.

There is evidence to suggest that downward leaching played a role in crust consolidation. Mixture modelling and XRD analyses of aeolian sands deflated from Chott Fedjaj show that they contain 80 per cent gypsum at most (Table I). All samples taken from the surface of gypsum crusts show gypsum concentrations much lower than the sands from Chott Fedjaj, suggesting depletion of gypsum at the surface; however, the samples from within the Roman farm deposit are nearly pure gypsum (Table I). In addition, the deposit must initially have contained some aeolian bedding structures as the consolidated gypsum dunes to the south of Chott Djerid do today, but none are observed in the quarry sections, presumably because solution and reprecipitation of gypsum has obliterated them.

These observations could be explained by the following consolidation scenario. Deposition of sands that contain gypsum and minor quartz occurs behind a topographic barrier. The sands are subsequently consolidated

Table I. Gypsum concentration of samples analysed by XRD. The location of the sample sites is shown in Figure 4.

Sample site	Description of site	Gypsum concentration (%)
1	Crust from below midden at Roman farm site	97
2	Crust from base of gypsum quarry shown in Figure 2B	100
3	Sand dune, Chott Fedjaj	70
4	Sample of surface of crust, sandflat	30
5	Sample of surface of crust, sandflat	31
6	Aeolian sand, sandflat	57
7	Consolidated aeolian sand, sandflat	20
8	Consolidated aeolian sand, sandflat	30
9	Aeolian sand, sandflat	35
10	Sample of surface of crust, Sidi Bou Hellal	10
11	Sample of surface of crust, Sidi Bou Hellal	16

by dissolution, downward transport and reprecipitation of gypsum. The process appears to lead to concentration of gypsum within the deposit, and not transport through the deposit as Watson (1988) suggests. The limited downward transport may well be controlled by the initially high amounts of gypsum within the deposit leading to rapid saturation of percolating waters. This leaching will gradually lead to a decrease in gypsum at the surface, and once the gypsum content of the crust falls below a certain concentration threshold, the crust's binding capacity is reduced to a level that allows the predominantly quartz sands to be reworked by the wind. The deflation threshold has not been estimated in this study but could be determined by studying the gypsum concentration of the yardangs outlined above (Figure 7C).

This model involves gradual accretion of surficial gypsum deposits, with each aeolian addition to the deposit contributing some of its gypsiferous material, but little quartz. The model could also be used to explain the current accretion of gypsum crusts on the sandflat, with vegetation forming the sand traps creating nebkas, phreatophyte mounds and spring mounds that are subsequently consolidated and leached; however, in this area the water table is near the surface and upward movement of gypsum cannot be discounted. As the mode of consolidation of gypsum deposits is closely related to the position of the water table, the evidence concerning consolidation processes presented here may only apply to surficial crusts that are not influenced by it.

This model of consolidation is corroborated by other evidence. Table I shows that the gypsum content of aeolian sand samples appears to decrease further away from the source on Chott Fedjaj (Figure 4). The mixture modelling, however, shows a more complex picture, with both gypsum- and quartz-rich sands present on the sandflat (Figure 8, regions C and D). Field studies show that the gypsum-rich sands are unconsolidated and thus probably represent aeolian material that has not been previously trapped. Sands that contain more than 30 per cent quartz (i.e. areas that contain more quartz than the sands in the immediate vicinity of the source), however, are found in both consolidated, eroded and unconsolidated forms.

Wind direction in Roman times

The gypsiferous sands are currently deflated from Chott Fedjaj and transported in a southwesterly direction. However, for these sands to be deposited against the glacis on the southern flanks of Djebel Sidi Bou Hellal, the predominant wind would have been an easterly. If the drier parts of the mudflats of Chott Fedjaj have remained the source of aeolian gypsum deflation, as they appear to be today, then there must have been a change in the predominant wind direction by about 45° to the southwest since late Roman times. An ever greater change in wind direction is needed if one considers the possibility that the gypsiferous sands may have come from the more extensive areas of gypsiferous mudflats of Chott Djerid. No deflation zones have been recognized on Chott Djerid, but the region is vast and in many areas the mudflats do not contain large gypsum crystals and thus would not develop the lag that allows the recognition of deflation zones on Chott Fedjaj. The inferred change in wind regime is surprising for although there has been much research on climate change in North Africa since Roman times, there is little evidence for it (Mattingly, 1995).

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